Flavor Observations with Supernova Neutrinos

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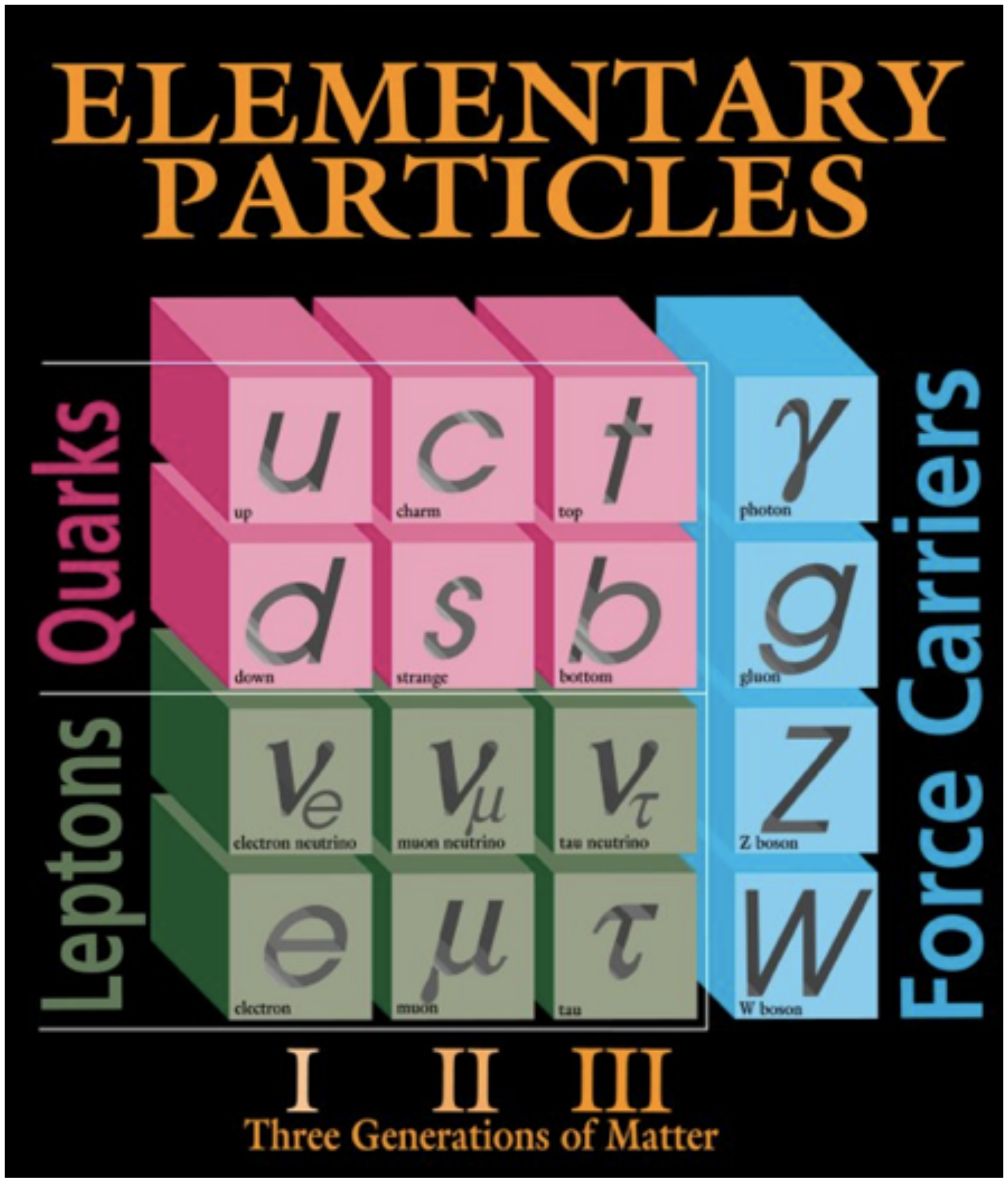
Welcome!

- Thank you very much for coming.

Neutrino messengers



- All three flavors of neutrinos and their antineutrinos (electron, mu, tau) are radiated in core collapse supernovae.
- **Neutrinos cary unique flavor information all the way to earth.**
- Nu capture on n to make p, anti-nu convert p to n. Flavor info related to composition of SN matter and nucleosynthesis.
- Note, neutrinos are somewhat forgetful messengers because of oscillations.

Neutrino Spectra

- The stronger a neutrino interacts, the longer it stays in equilibrium with matter, so that it is emitted at lower densities and temperatures.
- Electron flavored neutrinos and antineutrinos have both charged and neutral current interactions.
- Mu and tau neutrinos have only neutral current interactions.

ν, $\bar{\nu}$ and Weak Magnetism

- Time reversal symmetry implies neutrino-nucleon and antineutrino-nucleon cross sections are equal at very low energies.
- Difference is recoil order E_ν/M times large magnetic moment. This weak magnetism correction makes antineutrino cross sections about 10% smaller than neutrino cross sections for SN energies.

Neutrino energies

Weak magnetism

— Anti-mu and anti-tau neutrinos

— Anti-electron neutrinos $\bar{\nu}_e + p \rightarrow n + e^+$

— Mu and tau neutrinos

Energy

Protoneutron star is neutron rich

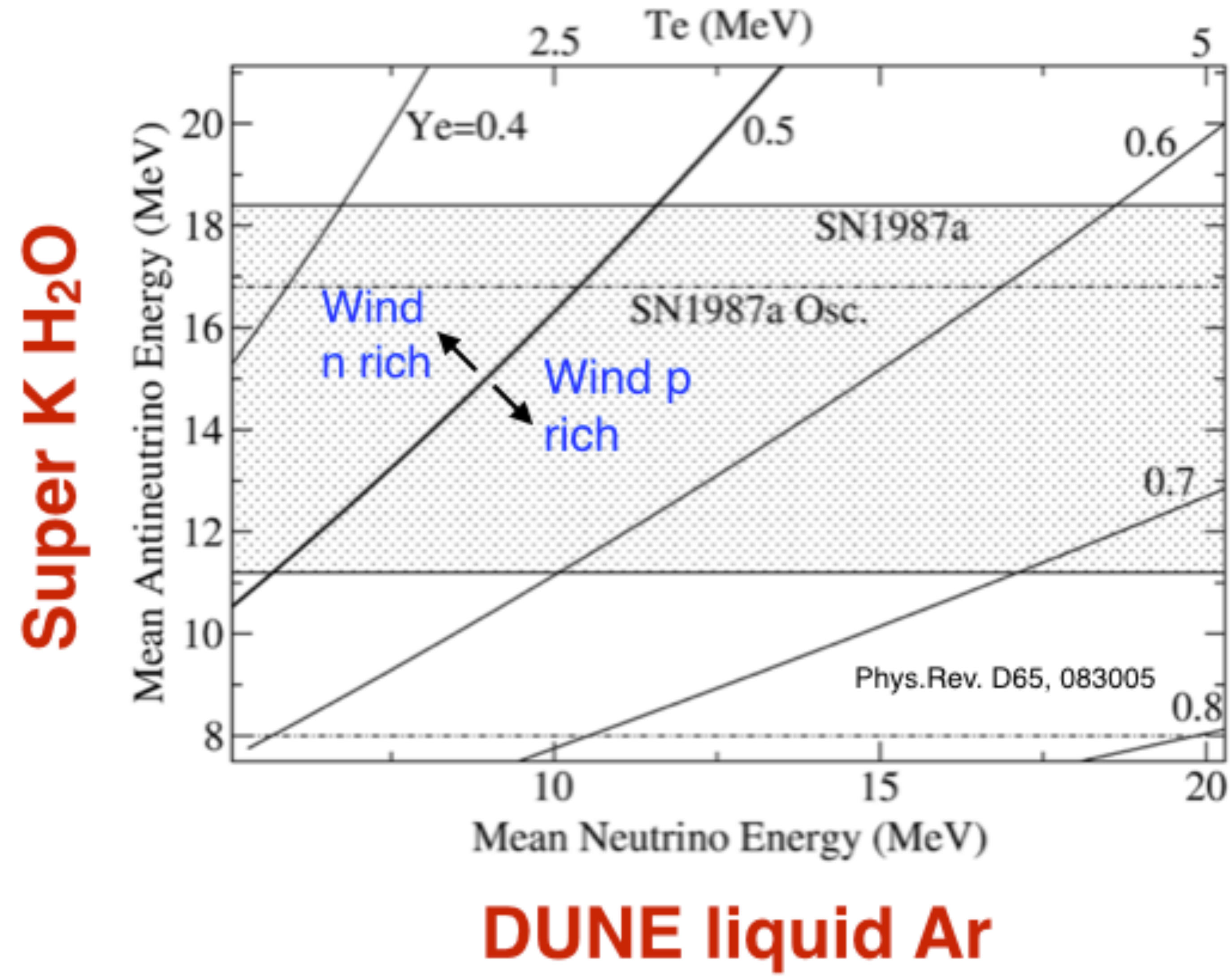
— Electron neutrinos $\nu_e + n \rightarrow p + e$

SN neutrinos and r-process nucleosynthesis

- Half of heavy elements (including gold) are believed made in the rapid neutron capture process. Seed nuclei captures many n and decay.
- Important possible site for the r-process is the neutrino driven wind in core collapse supernovae.
- Ratio of neutrons to protons in wind set by capture rates that depend on neutrino / anti-neutrino energies.

$$\nu_e + n \rightarrow p + e$$

$$\bar{\nu}_e + p \rightarrow n + e^+$$



Important to measure energy of both anti-nu (SK) and neutrinos (liquid argon DUNE).

ΔE depends on some nuclear physics including symmetry E at low densities.

However, present SN simulations find too few neutrons.

Supernova Quantum #s

- Total # of SN neutrinos radiated 10^{58}
- Baryon # of neutron star is 10^{57}
- Electron # of NS is 10^{56}
- Muon # of NS is 10^{55}
- Tau # of hot proto-NS is 10^{54}
- Strangeness of NS is ??
- SN radiates ~ 10^{57} more electro neutrinos than electron antineutrinos and ~10^{55} more muon antineutrinos than muon neutrinos. —> Macroscopic changing of the generations.
- Tau neutrinos and antineutrinos produced in pairs but antineutrinos leave faster, leaving star neutrino rich.

Workshop Goals

- Discuss supernova neutrinos and in particular features that depend on neutrino flavor (electron, mu, or tau) and if it is a neutrino or antineutrino.

- Motivate experimental work to better prepare us to observe supernova neutrinos and antineutrinos and their flavors, so that we can obtain the maximum information from next galactic SN.

- Motivate theoretical work to improve predictions of neutrino spectra and help separate uncertainties from astrophysics, nuclear physics, and neutrino physics.

- Help bring together astrophysics, nuclear physics, and neutrino physics communities.

Nuclear physics

- How well can we calculate neutrino interactions and properties of matter near the neutrinosphere? Can we provide useful theoretical error bars?

- What is the equation of state at different densities and temperatures?

- How do complex nuclear-pasta phases impact the neutrino opacity and spectra?

- What are neutrino interactions at high densities?

- Are there phase transitions at high densities? and how might they impact neutrino signals?

Astrophysics

- How to observe neutronization burst?
- What is the delay to explosion?
- What is the density profile of the progenitor star and the mass accretion rate?
- How to see late(?) black hole formation?
- Can we see the SASI (standing accretion shock instability) leading to oscillations in neutrino signal?
- Can we see “LESA”: dipole asymmetry in anti-nu_e vs nu_e fluxes from convective transport of lepton number?
- How does the protoneutron star cooling signal at late times depend on EOS, possible phase transitions, nu opacity at high densities…?

Neutrino Physics

- What do we understand about collective neutrino oscillations?

- Sensitivity of neutrino signal to $\boldsymbol{\nu}$ mass hierarchy?

  Degeneracy of this signal with other astrophysics, nuclear physics, or neutrino physics?

- Impact of turbulence / shocks on neutrino-matter oscillations?

- Sensitivity to beyond standard model physics?

Observational questions

- What fraction of time are different detectors live? How long will they be running? Is there any coordination?
- How well will electron anti-neutrinos be measured?
  - How well will electron neutrinos be measured?
  - How well will mu and tau neutrinos be measured?
  - How well will the total energy in active neutrinos be determined?
- How well will the mean energy of the anti-nu_e be determined? the mean nu_e energy? the nu_x energy? As a function of time?
- How well can small features in the neutrino spectrum, possibly from osc, be determined?
- How cleanly can different event types be separated?
- What unexpected signals have you considered?

Next generation detectors

- What can we learn from combining the information from different detectors? How can we optimize global sensitivity?
- What are the requirements for next-generation detectors in order to maximize physics/astrophysics output for a supernova observation?
- What signatures of physics and astrophysics are robust? Experimentalists would like fluxes with robust physics signatures in them, in order to test whether a given detector design would be sensitive to the physics.
- What theoretical / simulation input would experimentalists like?
- What is known about neutrino-nucleus interactions in the supernova neutrino energy range for different SN detector targets? What theoretical calculations are needed? What experimental measurements are needed?

Status of SNEWS

- If there is a SN: how will we know? when will we know? who will know? how well will event be localized?
- Will we see this galactic SN in photons? Will we see it in gravitational waves? Could we have a silent SN? Did we miss any galactic core collapse events since SN1987A? Are there any massive stars missing?
- Will we see the neutron star? Where is NS in SN1987A?
- Could we see pre supernova neutrinos?
- Please DO NOT believe the theoretical SN models!

Observational Goal

- We are not waiting decades just to confirm a nearly complete and almost certainly correct theory.

- Instead we are hoping to record enough detailed raw information to allow the first characterizations of a whole new field that just exploded into being.

What comes next?

- Mainz workshop "Supernova neutrino observation", Oct. 9-13, 2017. See Thomas Janka

- Can we prepare theoretically and experimentally for a "SN drill": On Feb. 23, 2022 a 15 M_sun star will explode only 5 kpc away. What will each detector see? and what can we conclude? What important detectors or theory are we missing? Perhaps we could discuss this in a future meeting and write a white paper?

- How to build communities and collaborations? European, Japanese, JUNO, Super K, Hyper K, Ice Cube, DUNE…

- Would some kind of an INT/ Fermi Lab collaboration make sense? This could cover both SN neutrinos and neutrino-nucleus interactions….